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FLIGHT SIMULATOR VISUAL-DISPLAY DELAY COMPENSATION

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ABSTRACT

A piloted aircraft can be viewed as a closed-loop man-machine control system. When a simulator pilot is performing a precision maneuver, a delay in the visual display of aircraft response to pilot-control input decreases the stability of the pilot-aircraft system. The less stable system is more difficult to control precisely. Pilot dynamic response and performance change as the pilot attempts to compensate for the decrease in system stability. The changes in pilot dynamic response and performance bias the simulation results by influencing the pilot's rating of the handling qualities of the simulated aircraft. The study reported here evaluated an approach to visual-display delay compensation. The objective of the compensation was to minimize delay-induced change in pilot performance and workload. The compensation was effective. Because the compensation design approach is based on well-established control-system design principles, prospects are favorable for successful application of the approach in other simulations.

1. INTRODUCTION

Flight simulation is important in aircraft development because simulation permits pilot evaluation of proposed design features and operating procedures early in the development process. Flight simulation is also important in pilot training because simulation permits pilots to practice routine and emergency flight procedures safely and economically. A modern flight research and development simulator consists of a cockpit equipped with flight instruments and controls; subsystems to provide visual, motion, and other flight cues; and one or more digital computers. The computers solve the aircraft equations of motion and control and synchronize the various simulator subsystems. Figure 1 is a sketch of the cockpit and motion system of the Ames Research Center's Vertical Motion Simulator.

There is a trend toward the use of computer-generated imagery (CGI) systems to generate flight simulator out-of-the-window visual scenes. CGI visual systems promise important features including large field-of-view, multiple-observer viewpoint, ease of scene modification, and moving targets. CGI systems construct a visual display from a description of the scene stored in a computer. The image construction time, though short (~ 100 msec), introduces a delay into the pilot-aircraft system. Several authors (Gum and Albery 1977; Larson and Terry 1975) have reported simulation problems traced to time delays in visual system cueing. The multimillion dollar simulator evaluated by Decker (1980) was rated unsatisfactory for training

pilots to perform precision flight tasks - at least in part because of CGI delays. Delay in displaying aircraft response to pilot control input degrades the pilot's ability to perform precision maneuvers, such as those required in formation flying, precision landing approaches, and weapons delivery. Changes in pilot performance and dynamic response, caused by display delay, bias the results of an aircraft development simulation by influencing the pilot's rating of the handling qualities of the simulated aircraft (Crane 1980).

Ricard and Harris (1978, 1980) analyzed the data from an experiment in which an attempt was made to compensate for delays in flight simulator visual displays. Ricard and Harris (1978), referring to the experimental data, wrote:

All of them indicate that human controllers prefer a phase lead that gets larger with longer delays, but all indicate that in the range of 150 to 200 milliseconds of delay that the amount of lead that produces best performance has reached zero!....

Should these data be extended to shorter delays, we might suggest that for systems with delays of less than 150 to 200 milliseconds, a phase lag would be the preferred change of the display signals....

The latter conclusion and the suggestion that phase lag be used to compensate for delays of less than

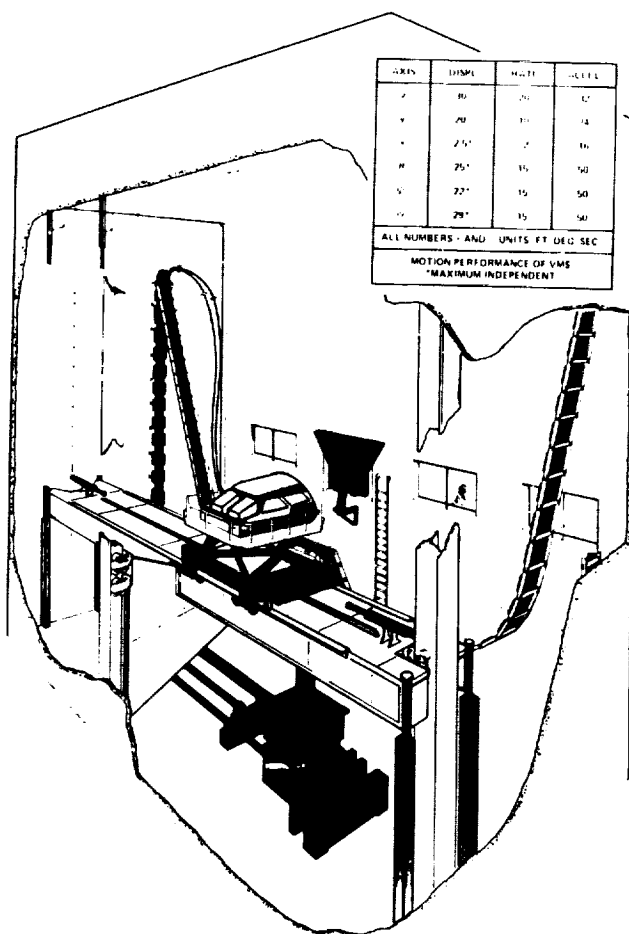


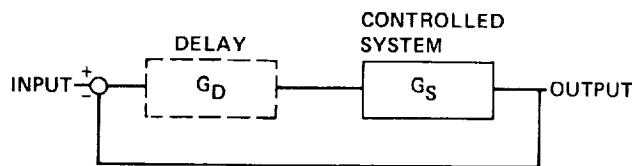
Fig. 1. The Vertical Motion Simulator at Ames Research Center; a six-degree-of-freedom motion system featuring 60 ft of vertical travel.

150 to 200 msec contradict conventional control-system design methods, which call for phase-lead compensation. The objective of the study reported here was to evaluate an approach to visual-display delay compensation that is based on conventional control-system design principles.

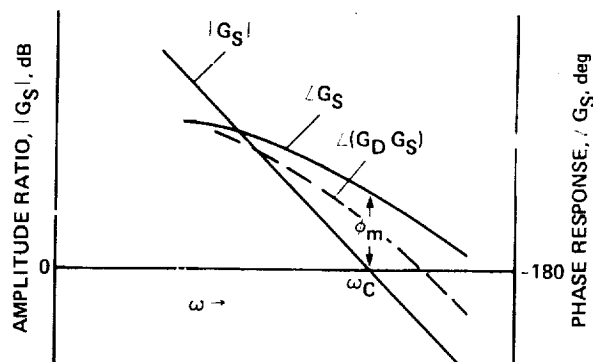
2. CONTROL-SYSTEM DELAYS - ANALYSIS AND COMPENSATION

The effects of time delay in closed-loop control systems can be readily determined by conventional control-system design methods. Figure 2a is a block diagram of a simple control system; Fig. 2b is a sketch of the open-loop transfer function of the system. The sketch identifies two important system parameters: crossover frequency (ω_c) and phase margin (ϕ_m).

Crossover frequency is that frequency at which the transfer function amplitude ratio "crosses" from greater than unity to less than unity (i.e., crosses the zero-decibel line). Crossover frequency is a measure of system bandwidth or



(a) BLOCK DIAGRAM



(b) TRANSFER FUNCTION

Fig. 2. Closed-loop control system.

responsiveness. Phase margin is defined as the amount by which the system phase angle at ω_c exceeds -180° . Phase margin is a measure of system stability. Figure 2 also illustrates the change in the system open-loop transfer function when a delay is inserted into the system. The delay transfer function G_D has an amplitude ratio that is identically 1 and a phase ϕ_d given by the expression $\phi_d = \omega t_d$ (where ω is frequency and t_d is the delay). The effect of the delay is to decrease the phase margin and stability of the system.

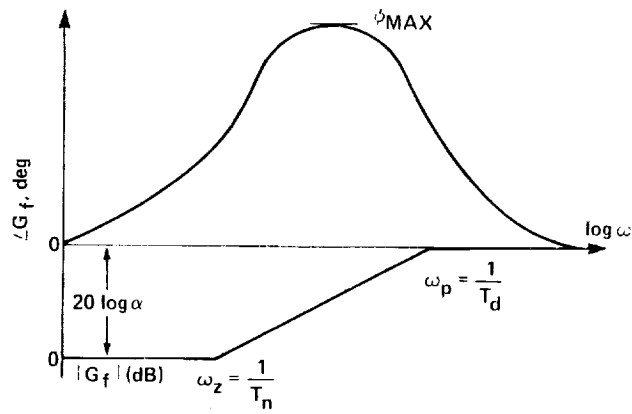
Figure 3 is a sketch of the characteristics of the lead filter, G_f ; $G_f = (T_n S + 1)/(T_d S + 1)$. The following features of the filter characteristics are important in the following sections of this paper:

1. Filter phase lead is a function of frequency and the maximum phase lead is a function of filter pole-zero separation.
2. The filter provides relatively little lead at frequencies less than ω_z .
3. Filter amplitude ratio is a function of frequency.
4. The filter "gain distortion," defined here as the ratio $|G_f(\omega_p)|/|G_f(\omega_z)|$, is proportional to filter pole-zero separation.

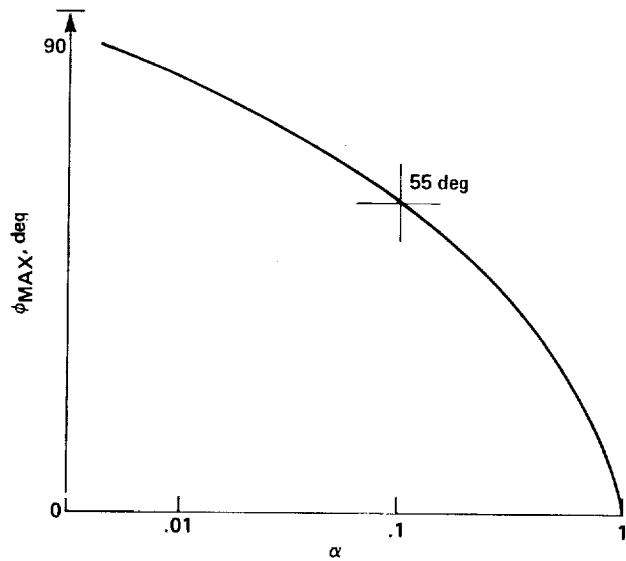
It is especially important to note that phase lead is purchased at the cost of gain distortion!

When the system transfer function is known, design of a lead filter to compensate for a specific delay, t_d , is straightforward. One need only locate the filter zero at ω_c and solve for T_d from Eq. (1), which equates the filter phase lead (ϕ_f) at ω_c to the delay phase lag at ω_c :

$$\phi_f|_{\omega=\omega_c} = \tan^{-1}\omega_c T_n - \tan^{-1}\omega_c T_d = \omega_c t_d \quad (1)$$



(a) FILTER AMPLITUDE AND PHASE RESPONSE



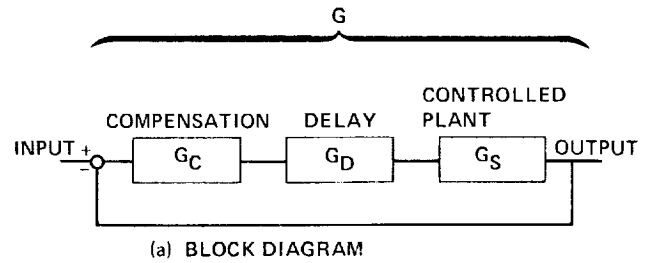
(b) MAXIMUM PHASE LEAD AS A FUNCTION OF $\alpha = T_d/T_n$

Fig. 3. Lead filter characteristics.

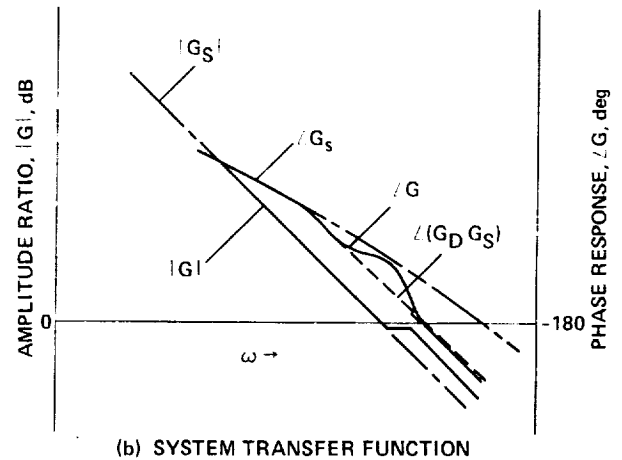
Figure 4 illustrates the design. This approach restores system stability while maintaining system accuracy (proportional to system gain) and responsiveness (proportional to ω_c). The increase in system gain at frequencies $>\omega_c$ is not normally a problem because system amplitude ratio and input and disturbance signal power usually decrease rapidly at frequencies $>\omega_c$.

An explanation of the results that led to the suggestion by Ricard and Harris (1978) that "...for systems with delays of less than 150 to 200 milliseconds, a phase lag would be the preferred change of display signals...." is apparent. The filters tested by Ricard and Harris (1978) were constrained by setting $T_n = \text{delay (seconds)}$. For shorter delays and typical aircraft dynamics, this constraint locates the filter zero at a frequency $>>\omega_c$ where the filter phase lead is not effective in restoring system phase margin.

The preceding review of a conventional method of control system compensation is strictly applicable to constant-parameter linear systems. Compensation of piloted control systems will be discussed



(a) BLOCK DIAGRAM



(b) SYSTEM TRANSFER FUNCTION

Fig. 4. Delay compensation with a lead filter.

following the description of the experimental tracking task.

3. THE EXPERIMENT

3.1 Tracking-Task Description

The tracking task used in the experiment is diagrammed in Fig. 5. The pilot's task was to manipulate a side-arm controller to maintain the simulated aircraft in a wings-level attitude in the presence of turbulence. In a particular trial, the blocks labeled "COMPENSATION" and "DELAY" were switched in or out as described under Experimental Procedures. Attitude error (or delayed or compensated and delayed attitude error) was displayed on an oscilloscope with a 5-in. CRT; no other instruments were used. The pilot was seated in a fixed-base (no motion) cab approximately 36 in. from the display. The cab was closed during the experiment to minimize pilot distractions. The controlled dynamics were the lateral dynamics used by Ricard and Harris (1978), in which the dynamics were described as modeling a light fixed-wing jet. The transfer function relating roll angle (ϕ_c) to control deflection (δ_a) is:

$$\frac{\phi_c}{\delta_a} = \frac{K(S^2/3.46 + 0.48S/1.86 + 1)}{S(0.16S + 1)(S^2/3.53 + 0.48S/1.88 + 1)} \quad (2)$$

To reduce controller sensitivity to a level rated acceptable in a study by Creer et al. (1959), the gain K was reduced to 10 from the 49.25 value used by Ricard and Harris (1978). Smith (1978), in a study that evaluated side-arm controller force gradients, also found that the lower gain

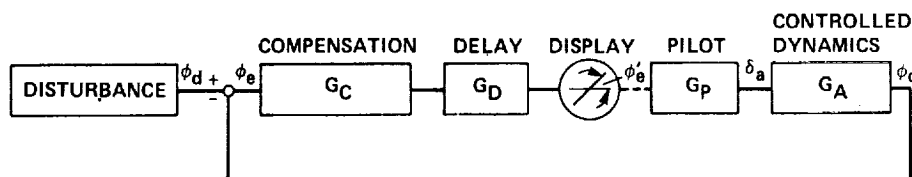


Fig. 5. Schematic diagram of tracking task used in the experiment.

was adequate over a wide range of force gradients and that the higher gain was rated too sensitive. The controller breakout and gradient forces were light; controller travel was limited to $\pm 15^\circ$. The disturbance signal was formed by summing six sine waves in the frequency range of 0.72 rad/sec to 6.54 rad/sec. The sine-wave amplitudes, listed in Table 1, were proportional to aircraft amplitude ratio. The composite signal approximated the aircraft response to turbulence; the maximum value of the disturbance was approximately 17° .

Table 1. Attitude Disturbance Specification

Component number	Frequency, rad/sec	Amplitude, deg
1	0.72	10.0
2	1.45	5.0
3	2.18	3.3
4	3.27	2.0
5	4.36	1.3
6	6.54	0.7

The simulation was implemented on a digital computer. Periodically, the computer sampled the pilot's control input, updated aircraft attitude and other system variables, and sent a signal to a digital-to-analog converter (DAC) to update the display. The period of the computations, T , was 12 msec. The period was chosen as small as possible to minimize the effective delay caused by the DAC zero-order hold. This delay, estimated at $T/2$ by Muira and Iwata (1963), and other computational effects are small relative to the delay tested; they were considered to be part of the baseline aircraft response.

3.2 Visual-Display Delay Compensation Design

In a piloted simulation, performance alone is an inadequate measure of compensation effectiveness because pilots will "work harder" to make up for delay-induced system deficiencies. The goal of display-delay compensation is to restore pilot performance and workload to baseline (no-delay) values. McRuer and Graham (1965) and others have shown that in tracking-task situations, the human operator dynamic response can be modeled as a quasi-linear system. In these models, a "describing function" models the linear part of the pilot response. The pilot-describing function concept is used here because it permits analysis of the man-machine control system under consideration using conventional control-system design methods and because pilot dynamic response is a sensitive measure of pilot workload.

In the piloted simulation considered, any change in system amplitude ratio resulting from display-delay compensation is undesirable. For example, an increase in gain shows up as an apparent

increase in disturbance intensity which tends to make attitude control more difficult. A decrease in gain tends to decrease tracking accuracy. However, some change in the system amplitude ratio is the price one must pay for the phase lead required to compensate for delay phase lag (Fig. 3).

The design rules for the display-delay compensation approach evaluated here are as follows:

1. Minimize compensation filter gain distortion by providing the minimum lead required, and by locating the lead at the frequency (ω_c) where the lead will be most effective in restoring system stability.
2. Distribute the resulting system gain distortion (over frequency) so as to minimize gain-change effects on system responsiveness ($\sim \omega_c$), pilot workload, and tracking accuracy.

The equation describing the display delay compensation scheme evaluated is

$$G_c = K_D \cdot \frac{T_n S + 1}{T_d S + 1} \quad (3)$$

The filter zero was placed at $\bar{\omega}_c$, the average crossover frequency attained by a group of pilots in an earlier study by Crane (1980). The small pilot-to-pilot variability in ω_c noted in the earlier study had suggested that a single filter might be effective for each of a group of pilots. The filter time constant, T_d , was computed from Eq. (1) to restore system phase margin. The gain distribution parameter, K_D , was chosen such that the filter gain at ω_c was unity. A reduction in system gain (and tracking accuracy) at frequencies $< \omega_c$ is accepted in order to reduce the increase in system gain (and disturbance intensity) at frequencies $> \omega_c$.

3.3 Subjects and Training

The subjects were five experienced helicopter pilots with recent flight time in military reserve or commercial helicopters. Before beginning the experiment, the pilots were briefed about the objective of the study. They were asked to maintain tight wings-level attitude, as if they were on a landing approach on a gusty day. Helicopter pilots were selected for the experiment in an attempt to insure that each pilot was experienced in aggressive attitude control. With one exception, the pilots primarily flew light utility-type helicopters. Pilot 5 primarily flew large, cargo-type helicopters.

To begin his training, each pilot observed the displayed response of the aircraft to the disturbance without attempting control. Each pilot then familiarized himself with the controller and

controlled dynamics by manipulating the controller and observing the aircraft response in several "no-disturbance" trials. Four trials at each experimental condition completed each pilot's training. Results of a related earlier study (Crane 1980) indicated that this training was adequate for experienced, motivated pilots.

3.4 Experimental Procedure

There were three experimental conditions: BASELINE, DELAYED, and COMPENSATED; they differed only in the processing of the aircraft attitude error signal, ϕ_e (Fig. 5). During BASELINE trials, attitude error was displayed on the oscilloscope without further processing ($G_C = 1$, $G_D = 1$). Note that the simple display used in the experiment was dictated by the need to acquire baseline data in order to judge compensation effectiveness. During DELAYED trials, the attitude error signal was delayed 0.108 sec before being displayed. During COMPENSATED trials, the attitude error signal was filtered in accordance with Eq. (3) and then delayed 0.108 sec before being displayed.

Each pilot flew eight trials at each condition. A trial consisted of a 35-sec "warm-up" followed by a 34-sec data-collection period. To minimize transfer effects (Poulton 1967), the order of the experimental conditions was counterbalanced and each trial was preceded by the warm-up period. Pilots were not informed of the order of testing. Care was taken to minimize pilot fatigue. Each pilot flew three groups of four trials on each of 2 consecutive days. After each trial, the pilot was rested for about 90 sec. After each group of four trials, pilots were alternated or given a 15-min break, during which time they were free to move about outside the cab. The data presented are averages over the last four trials at each experimental condition.

4. RESULTS

4.1 Pilot Performance

The objective of the compensation tested was to minimize any change in pilot performance and workload caused by display delay. The attitude error signal (ϕ_e , Fig. 5) was squared and integrated over each trial as a measure, integral-squared error (ISE), of pilot performance. Average (over trials) integral-squared error (\overline{ISE}) is plotted versus experimental condition in Fig. 6.

When averaged over pilots, \overline{ISE} was 38% larger for the DELAYED condition than for the BASELINE condition. The average increase in \overline{ISE} was reduced to 19% for the COMPENSATED condition. The BASELINE-DELAYED differences and the BASELINE-COMPENSATED differences were tested for statistical significance using a matched (by pilot) t-test. The tests confirmed that the differences measured are statistically significant at the 0.01 level, which means that the probability that chance variation accounts for the differences observed is less than 0.01. Table 2 summarizes the results of the matched t-tests.

Another performance measure is also of interest because although ϕ_e is attitude error, ϕ_e'

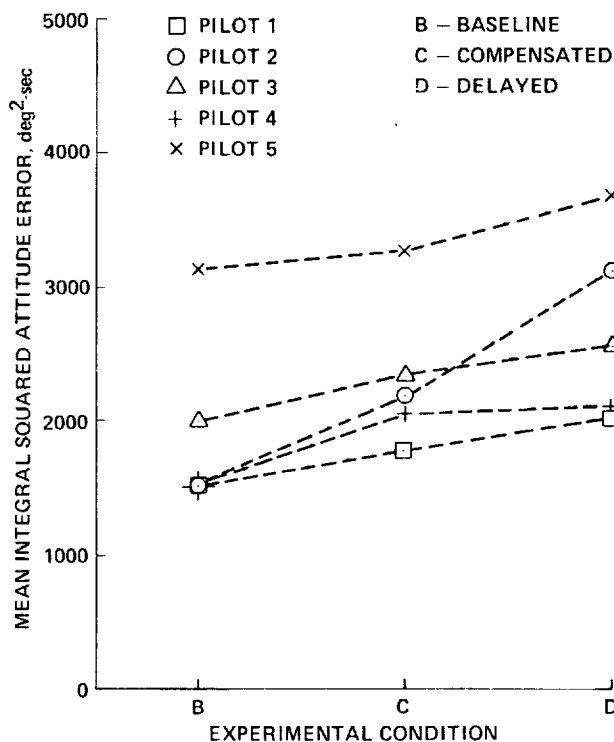


Fig. 6. Mean integral squared attitude error as a function of experimental condition.

(Fig. 5) is the signal displayed to the pilot. ϕ_e' was also squared and integrated over each trial. The average (over trials) integral squared ϕ_e' , \overline{ISEP} , is plotted versus experimental condition in Fig. 7. When averaged over pilots \overline{ISEP} (like \overline{ISE}) was 38% larger for the DELAYED condition than for the BASELINE condition. However, the average increase in \overline{ISEP} was reduced to 11% for the COMPENSATED condition. The compensation gain characteristic reduces the amplitude of low frequency signals (by approximately 15%) which accounts for the difference between \overline{ISE} and \overline{ISEP} .

4.2 Pilot Dynamic Response

The pilot-describing function was computed using the program described by Shirachi and Shirley (1977). The program computes the pilot's average (over the trial) amplitude and phase response at each disturbance frequency. Pilot phase response summed over the six disturbance frequencies and averaged over trials, \overline{SUMPH} , is plotted versus experimental condition in Fig. 8.

The average (over pilots) decrease in lag (increase in lead) between BASELINE and DELAYED conditions was 28.6°. A matched t-test again confirmed that the BASELINE-DELAYED difference was statistically significant at the 0.01 level (Table 2). The increase in pilot phase lead observed is consistent with the conventional control-system design approach to delay compensation, that is, to provide lead to restore phase margin. However, the increase in pilot lead is an indication of an increase in pilot workload (McRuer 1973), which would bias the results of a simulation by influencing the pilot's rating of the handling qualities

Table 2. Summary of T-Test Results

Measure*	BASELINE-DELAYED comparison			BASELINE-COMPENSATED comparison		
	Average difference	T-statistic	P value†	Average difference	T-statistic	P value†
\overline{ISE} (deg ² -sec)	-745	3.53	0.01	-384.4	4.3	0.01
\overline{ISEP} (deg ² -sec)	-745	3.53	0.01	-213.	2.81	0.025
\overline{SUMPH} (deg)	-28.6	4.63	<0.01	-9.3	0.927	>0.10 (N.S.)
$\bar{\phi}_m$ (deg)	6.7	6.63	<0.01	-4.49	1.71	>0.05 (N.S.)
$\bar{\omega}_c$ (rad/sec)	0.06	0.38	0.726 (N.S.)	0.28	1.9	>0.05 (N.S.)

*The measures are defined in the text.

†The P value is the probability that the observed difference is a result of chance variation; P values greater than 0.05 are considered not significant (N.S.).

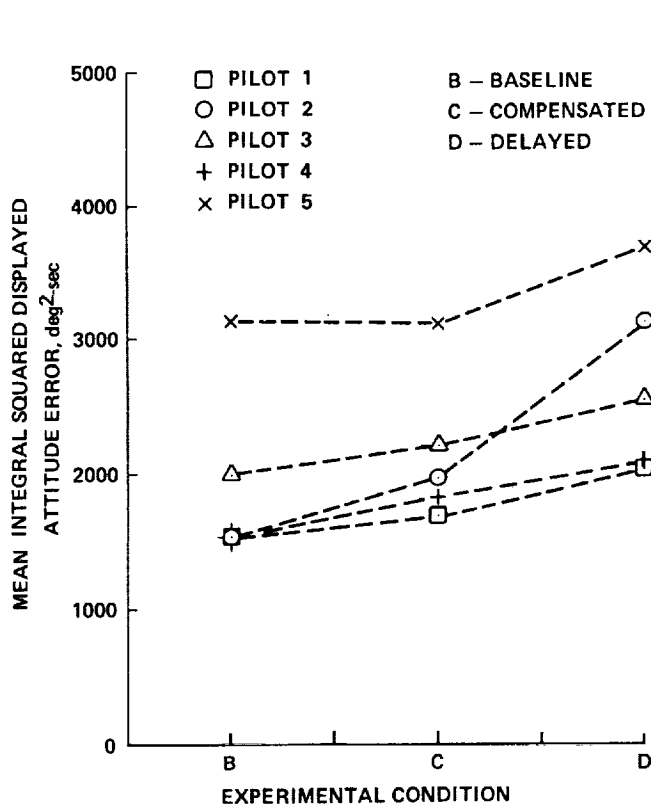


Fig. 7. Mean integral squared displayed attitude error as a function of experimental condition.

of the simulated aircraft. The average increase in lead was reduced to 9.3° for the COMPENSATED condition. The BASELINE-COMPENSATED difference in \overline{SUMPH} is not statistically significant; that is, the probability is relatively high that chance variation accounts for the difference observed. Comparison of Figs. 7 and 8 indicates that pilot performance and phase lead are highly correlated — better performance is associated with increased phase lead (increased effort).

4.3 Pilot/Aircraft-System Phase Margin and Crossover Frequency

The open-loop transfer function G was computed from eq. 4.

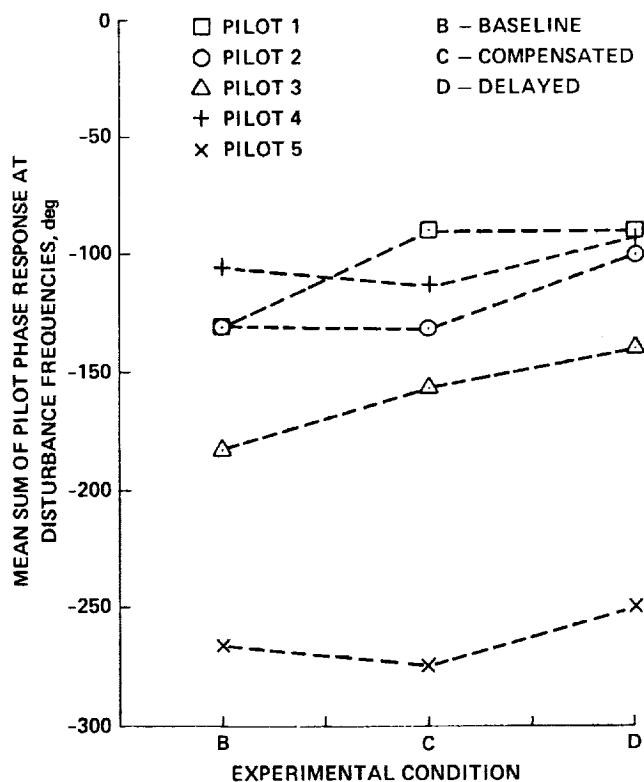


Fig. 8. Mean sum of pilot phase response at disturbance frequencies as a function of experimental condition.

$$G = G_C G_D G_P G_A \quad (4)$$

where

$$G_C = \begin{cases} 1 & \text{Condition B, D} \\ 0.85 (0.555S + 1) / (0.372S + 1) & \text{Condition C} \end{cases}$$

$$G_D = \begin{cases} 1 & \text{Condition B} \\ \exp(-0.108S) & \text{Condition C, D} \end{cases}$$

G_P = pilot describing function (measured)

G_A = aircraft transfer function [Eq. (2)]

S = Laplace transform operator

Crossover frequency and phase margin were computed by interpolation of the open-loop transfer function data.

Average (over trials) pilot/aircraft-system phase margin, $\bar{\phi}_m$, is plotted versus experimental condition in Fig. 9.

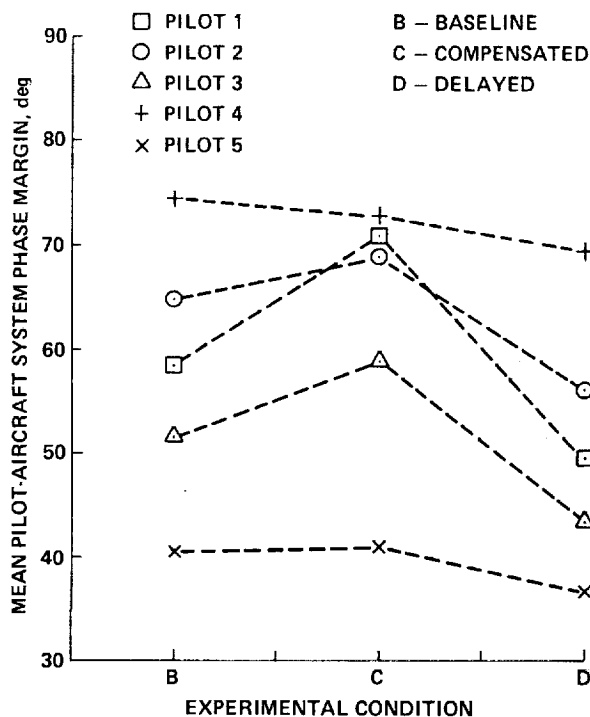


Fig. 9. Mean pilot/aircraft-system phase margin as a function of experimental condition.

When averaged over pilots, the BASELINE-DELAYED difference is 6.7° . The decrease in phase margin is an indication of a decrease in system stability, which makes the tracking task more difficult. A matched t-test confirmed that the BASELINE-DELAYED difference was statistically significant at the 0.01 level. The average (over pilots) BASELINE-COMPENSATED difference is -4.5° , which indicates the compensated system is slightly more stable than the baseline system. However, the difference is not statistically significant.

Average (over trials) pilot/aircraft-system crossover frequency $\bar{\omega}_c$ is plotted versus experimental condition in Fig. 10. When averaged over pilots, the BASELINE-DELAYED and the BASELINE-COMPENSATED differences are not statistically significant. The plot indicates that the value of $\bar{\omega}_c$ (1.8 rad/sec), assumed before the experiment in order to choose compensation parameters, was reasonable.

4.4 An Alternative View of the Data

Figure 11 is a composite of the strip-chart record of the last trial at each experimental condition for Pilot 1. This figure is included to illustrate the raw data underlying the measures of performance, workload, and stability — that were used

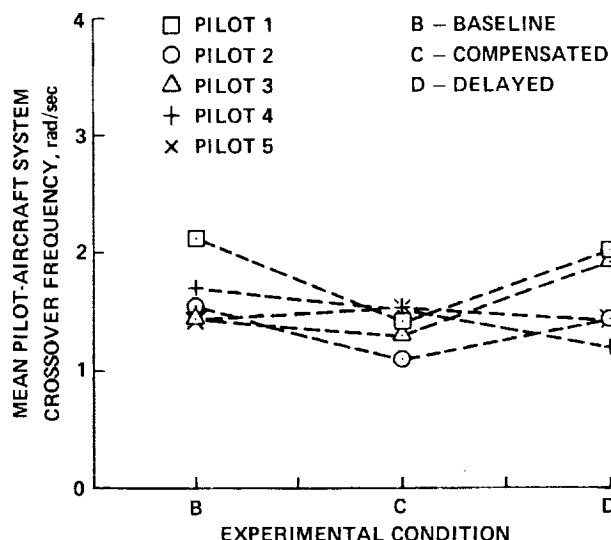


Fig. 10. Mean pilot/aircraft-system crossover frequency as a function of experimental condition.

to quantitatively evaluate the experimental data. The signals plotted are "attitude due to disturbance" (ϕ_d), "attitude due to control" (ϕ_c), "pilot control input" (δ_a), and "displayed attitude error" (ϕ_e). As noted earlier, each trial consisted of a 35-sec warm-up period followed by a 34-sec data-collection period. The pilot's task was to zero the displayed attitude error, in which case the ϕ_c trace would match the ϕ_d trace. Relative to BASELINE and COMPENSATED, the DELAYED data exhibit larger errors (points 1, 2), larger control inputs (range 3), and evidence of increased difficulty in achieving precise control (points 4, 5, 6, and 7). Similar effects in other trials were responsible for the differences (in performance, workload, and stability) between experimental conditions previously noted.

5. CONCLUDING REMARKS

A piloted aircraft can be viewed as a closed-loop man-machine control system. From this viewpoint it is clear that when a simulator pilot is performing a precision maneuver, similar to the tracking task discussed above, a delay in the visual display of aircraft response to pilot-control input has a number of deleterious effects. The immediate effect of the delay is to decrease the stability of the pilot-aircraft system. The decrease in stability is indicated by a decrease in system phase margin, which is a standard measure of control-system stability. The less stable system is more difficult to control precisely; therefore, pilot dynamic response and performance change as the pilot attempts to compensate for the decrease in system stability. The changes in pilot dynamic response and performance bias the results of the simulation by influencing the pilot's rating of the handling qualities of the simulated aircraft.

From conventional control-system theory, the decrease in system phase margin ($\Delta\phi_m$) is given by the product of system crossover frequency (ω_c) and

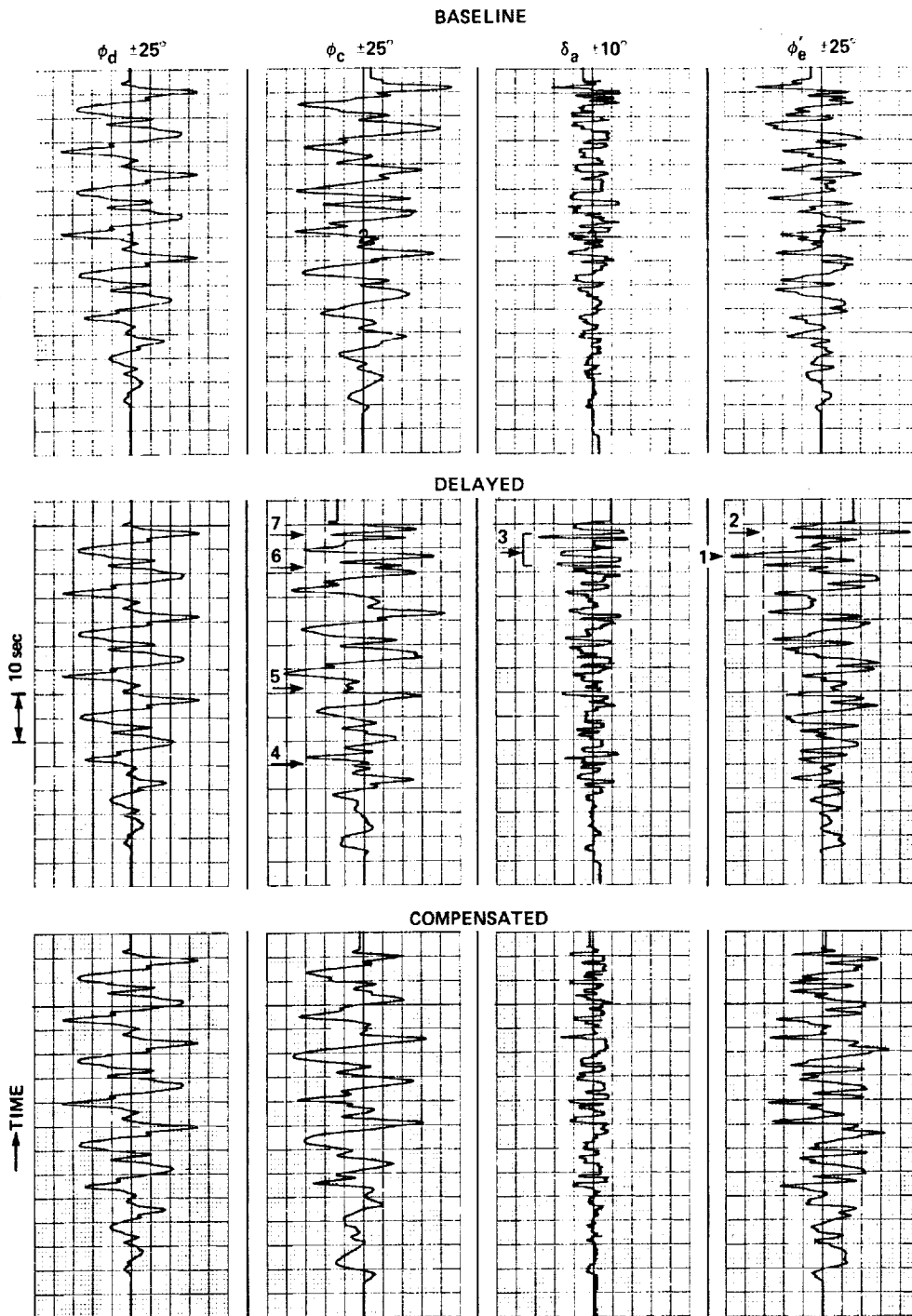


Fig. 11. Composite strip-chart record, Pilot 1; last trial at each experimental condition.

display delay (t_d). The importance of a delay increases with the ratio of (the resulting) $\Delta\phi_m$ to ϕ_m' , the design phase margin. Since ω_c and ϕ_m' are dependent on the specifics of a simulation (e.g., aircraft dynamics, display, controller, and task), the importance of a particular delay also depends on the simulation specifics. A given delay will be most troublesome when a pilot is attempting to precisely control a responsive aircraft (high ω_c) with relatively low inherent stability (small ϕ_m'). This analysis explains why, contrary to speculation in the literature, even

display delay shorter than 100 msec can be troublesome. Pilot delay perception limitations are not pertinent — the effect of display delay on system stability is the dominant consideration.

It is more difficult to compensate a man-machine control system for delay than a conventional non-piloted control system. In the man-machine system, any change in system amplitude ratio caused by delay compensation is undesirable. In the tracking task considered here, for example, an increase in system gain shows up as an apparent increase in

disturbance intensity, which tends to make the pilot's task more difficult. However, some change in the system amplitude ratio is the price one must pay for the phase lead required to compensate for the delay phase lag. Therefore, in a piloted system, it is important to attempt (1) to locate the exact phase lead required at the system crossover frequency where it will be most effective in restoring system stability, and (2) to distribute the attendant system gain distortion so as to minimize gain change effects on the pilot's task. In particular applications, system crossover frequency can be estimated as described here or by other methods.

The study reported here evaluated this approach to visual-display delay compensation in one specific simulation. The objective of the compensation was to minimize delay-induced change in pilot performance and workload. The compensation was effective. Pilot average performance was substantially (50%) improved. Pilot workload and system stability measures approached baseline (no-delay) values. Pilot-to-pilot differences in system crossover frequency were small enough that a single filter, based on average pilot dynamics, improved performance and/or workload measures for all pilots. Because the compensation design approach is based on well-established control-system design principles, prospects are favorable for successful application of the approach in other simulations.

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